

Cosmological constraints on Dark Matter models for collider searches

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ABSTRACT: Searches for Dark Matter at the LHC are commonly described in terms of simplified models with scalar, pseudo-scalar, vector and axial-vector mediators. In this work we explore the constraints imposed on such models from the observed Dark Matter relic abundance. We present these constraints over a range of mediator masses relevant for the LHC and for future, higher energy colliders. We additionally compute bounds from a photon line search for the decay of a pseudo-scalar mediator to di-photons that includes the mediator mass region near 750 GeV. Finally, we compare cosmological constraints with the reach of a possible future 100 TeV circular hadron collider, indirect, and direct detection experiments.

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1 Introduction

Data collected by the Planck mission [1] confirms that dark matter (DM) constitutes nearly 85% of the total matter content in the universe, corresponding to $\Omega_c \times h^2 = 0.12$. Under the assumption that both dark and visible matter in the universe are fundamental, DM should be described by a microscopic particle theory¹. The standard model of particle physics (SM) does not contain a viable DM candidate, therefore DM production must be associated with new physics. The discovery of this physics is among the most important goals in the field.

For a large class of models, DM phenomenology can be reduced to a set of well-defined DM-SM interactions. These interactions proceed through a mediator that connects dark matter to the particles of standard model. At the Large Hadron Collider (LHC), DM searches are performed using models that describe mediator-based interactions between DM particles and SM partons. These interactions can be classified by the types of messenger fields involved: scalar, pseudo-scalar, vector and axial-vector. Benchmark models for DM searches at the LHC typically have mediator couplings to the DM of $g_{DM} = 1$ [3, 4] and to the SM of $g_q = 0.25$ for vector and axial-vector mediators and $g_q = 1$ for scalar pseudoscalar mediators [3, 4]. For the center-of-mass energies produced at the LHC, sensitivity to the masses of the mediators and of the DM particles is generally O(TeV) for these couplings. Mediators potentially produced at the LHC are capable of probing a large variety of predicted models, including cosmological predictions of the relic density.

Cosmological constraints on these benchmark models can be understood in terms of the reach required to cover the full production phase space of the observed relic density. The

¹for a review see e.g. [2]

scale of the underlying new physics may be out of reach of the LHC, in which case a hadron collider with higher collision energy is needed. Many recent studies have explored the physics potential of a future circular collider (FCC) with a center-of-mass energy of 100 TeV [5–9]. We extend our studies of cosmological constraints to DM searches performed with this machine.

We additionally consider the expected bounds of other DM experiments relative to those of the LHC and FCC. The ultimate reach of direct detection experiments is expected to extend to the so-called “neutrino wall” [10–15]. We consider the bounds that direct detection experiments with such sensitivity may place on the simplified model framework used in collider searches. For the case of pseudo-scalar mediators, we consider the impact of projected bounds of indirect detection and photon line searches.

Our work contributes to the emerging program of DM studies at future colliders in the 100 TeV range [16–20]. Related studies using simplified models for constraining dark sectors at the LHC include Refs. [21–30]. We also refer readers to the recent summaries [3, 31] and references therein.

2 Simplified Models

DM searches at hadron colliders typically assume that DM particles are pair-produced from the collisions of visible sector particles – the SM quarks and gluons. In the scenarios studied here there are no direct interactions between the SM sector and the DM particles of the dark sector. Instead, DM-SM interactions are mediated by an intermediate degree of freedom – the mediator field. In general, four types of mediators (scalar S , pseudo-scalar P , vector Z' or axial-vector Z'') may be involved. The four corresponding classes of simplified models that describe the elementary interactions of these mediators with the SM quarks and DM particles (χ) are

$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2}M_{\text{Med}}^2 S^2 - g_{\text{DM}} S \bar{\chi}\chi - \sum_q g_{SM}^q S \bar{q}q - m_{\text{DM}} \bar{\chi}\chi, \quad (2.1)$$

$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2}M_{\text{Med}}^2 P^2 - ig_{\text{DM}} P \bar{\chi}\gamma^5\chi - \sum_q ig_{SM}^q P \bar{q}\gamma^5q - M_{\text{DM}} \bar{\chi}\chi, \quad (2.2)$$

$$\mathcal{L}_{\text{vector}} \supset \frac{1}{2}M_{\text{Med}}^2 Z'_\mu Z'^\mu - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu \bar{q}\gamma^\mu q - M_{\text{DM}} \bar{\chi}\chi, \quad (2.3)$$

$$\mathcal{L}_{\text{axial}} \supset \frac{1}{2}M_{\text{Med}}^2 Z''_\mu Z''^\mu - g_{\text{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5q - M_{\text{DM}} \bar{\chi}\chi. \quad (2.4)$$

The coupling constant g_{DM} characterizes the interactions of the messengers with the dark sector particles, which for simplicity we take to be Dirac fermions (χ and $\bar{\chi}$). The case of scalar DM particles is a straightforward extension of these results.

The coupling constants linking the messengers to the SM quarks are collectively described by g_{SM}^q ,

$$\text{scalar \& pseudo - scalar messengers :} \quad g_{\text{SM}}^q \equiv g_q y_q = g_q \frac{M_q}{v}, \quad (2.5)$$

$$\text{vector \& axial - vector messengers :} \quad g_{\text{SM}}^q = g_{\text{SM}}. \quad (2.6)$$

For scalar and pseudo-scalar mediators, the couplings to quarks are taken to be proportional to the corresponding Higgs Yukawa couplings (y_q), as in models with minimal flavour violation [32]. The g_q scaling factors are assumed to be flavour-universal for all quarks. For vector and axial-vector mediators, g_{SM} is a gauge coupling in the dark sector, which we also take to be flavour universal. The coupling parameters varied are thus g_{DM} and either g_q or g_{SM} , depending on the messenger.

In general, the simplified model description of the dark sector requires five parameters: the mediator mass M_{Med} , the mediator width Γ_{Med} , the dark particle mass M_{DM} , and the mediator-SM and the mediator-DM couplings, g_{SM} , g_{DM} . Our estimate of the mediator width, Γ_{Med} , uses the assumption that the DM particles and the mediator are the only additions to the SM particle content; this is known as the minimal width assumption.

3 Cosmological Constraints for Searches at the LHC

The **MadDM** tool [33] is used to compute the relic density. **MadDM** calculates the expected relic DM density in terms of $\Omega_c \times h^2$ for any **MadGraph** model provided [34]. The tool gives a numerical estimate of the expected relic density based on the standard model of cosmology for any model containing a DM candidate. The estimate is primarily based on the calculation of the cross-section of the $\chi\chi \rightarrow qq$ process, *i.e.* the annihilation of a DM pair into SM particles. For the four mediators explored in this study (generically, Φ), this leads to the annihilation process $\chi\chi \rightarrow \Phi \rightarrow qq$.

The expected values of $\Omega_c \times h^2$ are shown in Fig. 1 for the mass ranges reachable by the LHC in Run-1 for couplings $g_{\text{DM}} = g_{\text{SM}} = 1$. The expected Ω_c grows rapidly for $M_\chi < M_t$, which results from a reduced cross section for the $\chi\chi \rightarrow SM$ annihilation process. This feature is particularly strong for models with (pseudo-)scalar mediator due to the enhanced Yukawa couplings to heavy quarks. The expected Ω_c also decreases in the region $M_{\text{Med}} \sim 2 \times M_{\text{DM}}$, which results from a resonant enhancement in the annihilation cross section.

The pink curves in Fig. 1 correspond to $\Omega_c \times h^2 = 0.12$, which is the best fit from Planck satellite observations [35]. These curves appear (for $g_q = g_{\text{SM}} = 1$) in searches by the CMS Collaboration [36, 37]. The regions closer to the line $M_{\text{Med}} \sim 2 \times M_{\text{DM}}$ have lower values of $\Omega_c \times h^2$ and correspond hence to under-abundant DM production. The regions away from the line $M_{\text{Med}} \sim 2 \times M_{\text{DM}}$ have higher values of $\Omega_c \times h^2$ and correspond to DM overabundance.

Fig. 2 shows the predicted values of Ω_c for $g_{\text{SM}} = 0.25$ (labelled $g_q = 0.25$). These coupling values are currently recommended by the LHC DM WG [3, 4] and are used in a recent 13 TeV DM search by the ATLAS Collaboration [38]. The behavior of $g_{\text{SM}} = 0.25$ results are

similar to those of $g_{SM} = 1$: annihilation is enhanced for $M_{\text{Med}} \sim 2 \times M_{DM}$ and suppressed for $M_{DM} < M_t$. The expected relic density is smaller than that for $g = g_q = g_{SM} = g_{DM} = 1$ due to the decrease in annihilation cross section.

Compared to the constraints for the (axial-)vector mediators, the constraints for the (pseudo-)scalar mediators are, for low mass, closer to the line $M_{\text{Med}} \sim 2 \times M_{DM}$. This is attributed to the relatively narrow width of the (pseudo-)scalar mediators, and the Yukawa nature of its couplings to the SM particles. The behavior at $M_{\text{Med}} \sim 800$ GeV for the axial mediator is due to double-mediator production, which occurs when $M_{DM} \geq M_{\text{Med}}$ [39].

The results have also been cross-checked against an independent analytical estimate of the relic density and the results were found in agreement [25].

4 Cosmological Constraints for a 100 TeV Collider

A (hadron) collider with higher collision energy and mass reach would be needed if the scale of the new physics underlying DM production lies beyond the reach of the LHC [5]. At such collision energy, the sensitivity to M_{Med} typically extends up to few TeV (for the scalar and pseudo-scalar types) or > 15 TeV (for the vector and axial-vector types) [40].

The predicted relic DM density is shown in Fig. 3 for $g = 1$ over a wide mass range characteristic of the FCC. The region with small predicted values of $\Omega_c \times h^2$ lie mostly around the diagonal $M_{\text{Med}} \sim 2 \times M_{DM}$. This is because resonant annihilation of $\chi\chi \rightarrow SM$ is preferred for $M_{\text{Med}} \sim 2 \times M_{DM}$. Moreover, the constraint tends to align more closely to the diagonal for (pseudo-)scalar mediators than for (axial-)vector mediators, due to the narrower widths of the former.

In general, the results for these models indicate a cosmologically preferred region of masses up to $M_{\text{Med}} < 7 - 10$ TeV (for scalar and axial-vector mediators) and $M_{\text{Med}} < 40 - 65$ TeV (for vector and pseudo-scalar mediators). The bounds from $\Omega_c \times h^2 \leq 0.12$ are considered as a function of the couplings in Fig. 4. Although the shapes of the constraints do not change significantly for the couplings considered, the maximally allowed mass changes significantly, scaling in proportion with the coupling.

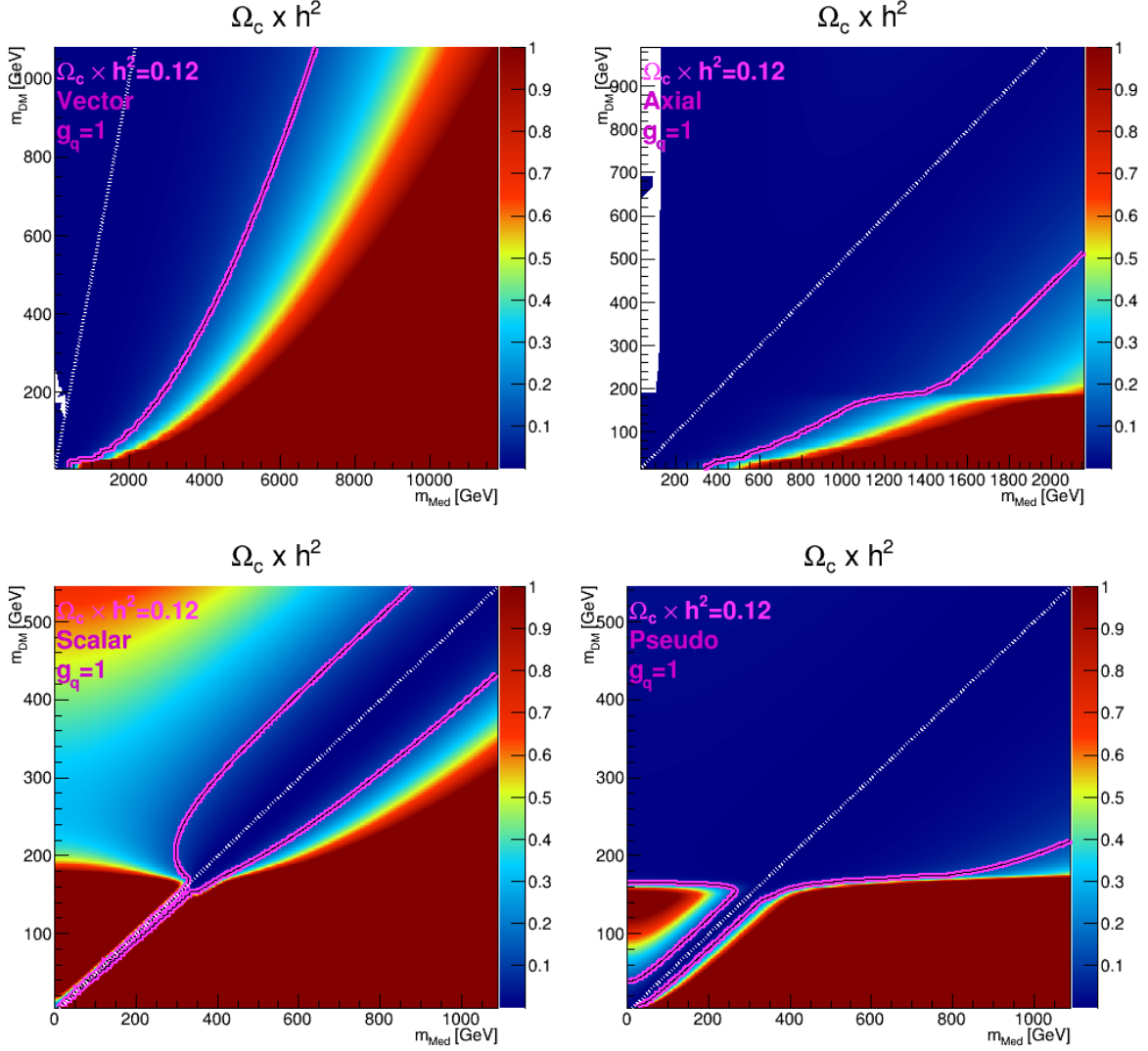


Figure 1. The predicted DM relic density for the vector, axial-vector, scalar, and pseudo-scalar mediators for coupling $g_q = g_{SM} = g_{DM} = 1$. The white dashed line corresponds to the region where $M_{\text{Med}} \sim 2 \times M_{\text{DM}}$. The pink curve denotes the masses for which the predicted relic DM coincides with the observed $\Omega_c \times h^2 = 0.12$ [1].

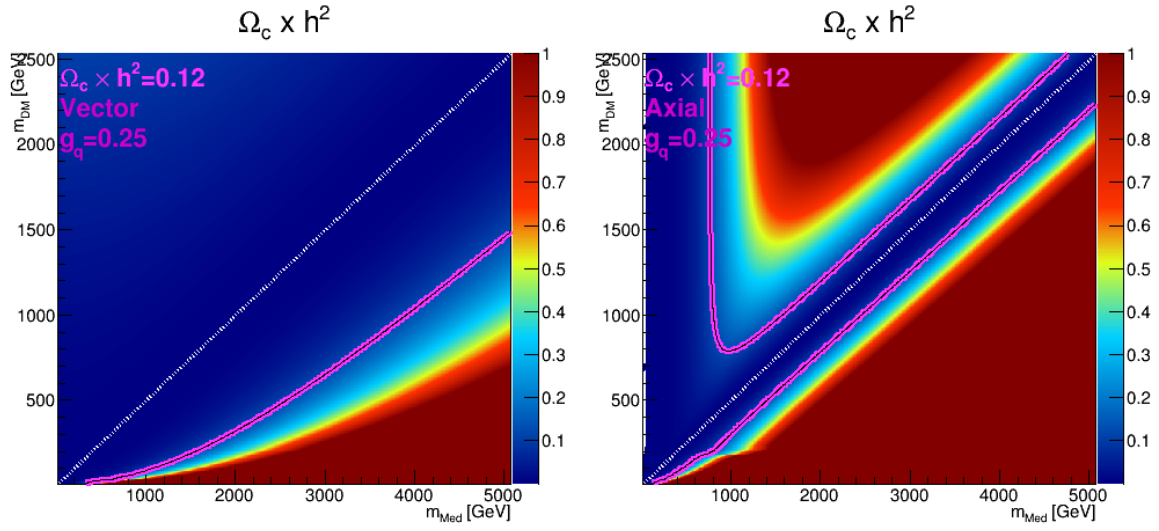


Figure 2. The predicted DM relic density for the vector and axial-vector mediators for coupling $g_{SM} = 0.25$ (labelled $g_q = 0.25$) and $g_{DM} = 1$. The white dashed line corresponds to the region where $M_{\text{Med}} \sim 2 \times M_{DM}$. The pink curve denotes the masses for which the predicted relic DM coincides with the observed $\Omega_c \times h^2 = 0.12$.

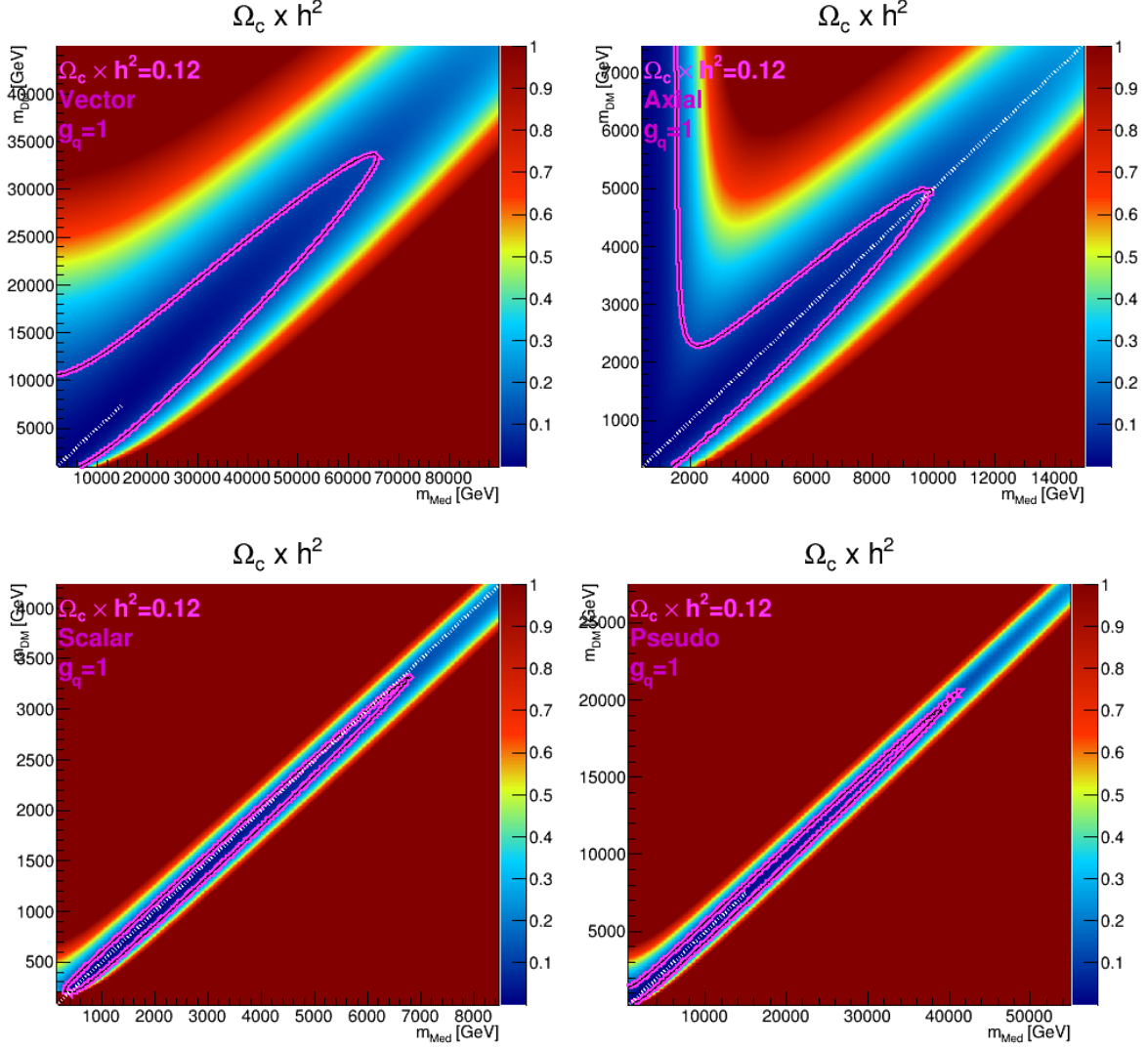


Figure 3. Predicted DM relic density for the vector, axial-vector, scalar and pseudo-scalar mediators for default coupling $g_q = g_{SM} = g_{DM} = 1$. The white dashed line corresponds to the region where $M_{Med} \sim 2 \times M_{DM}$. The pink curves denote the masses for which $\Omega_c \times h^2 = 0.12$.

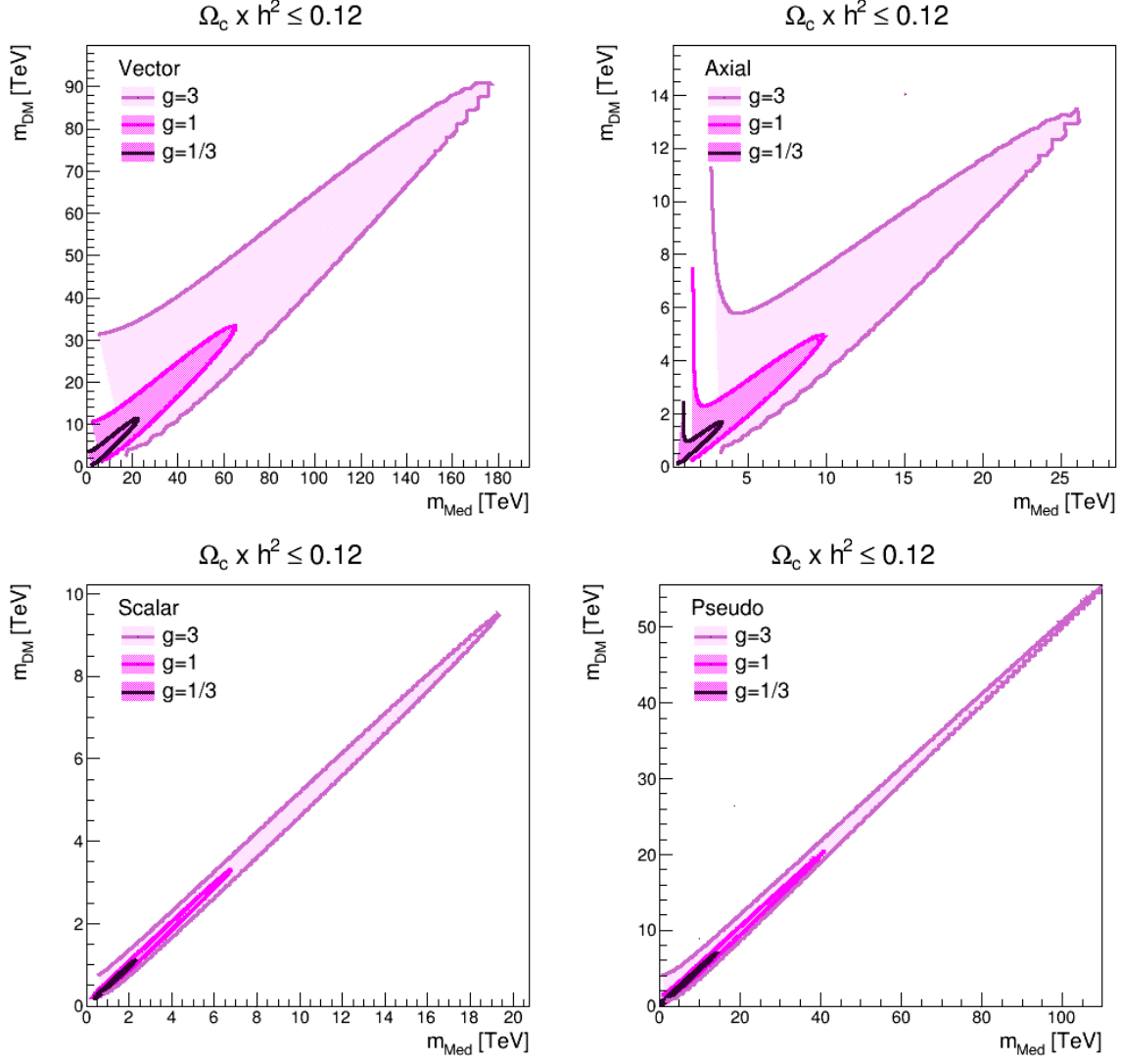


Figure 4. Predicted regions for $\Omega_c \times h^2 \leq 0.12$ for the vector, axial-vector, scalar and pseudo-scalar mediators for various couplings: $g_{DM} = 1/3, 1, 3$. The label g on the plots denotes g_{DM} , for all cases $g_q = g_{SM} = 1$.

5 Direct Photon search

The scattering cross section of a pseudo-scalar mediator is heavily velocity-suppressed at direct detection experiments. Because of this, we compare collider and relic constraints with bounds from indirect detection. We consider indirect detection bounds from searches for photons resulting both from the decay of SM particles produced in DM annihilation, and from those from direct mediator-to-photon production, *i.e.* “photon line” searches. Bounds from the latter are computed by considering the direct production of a pseudo-scalar mediator to photons through a top loop. The velocity averaged annihilation cross section to photons, $\langle\sigma v\rangle_\gamma$, can be expressed as [21, 41]:

$$\langle\sigma v\rangle_\gamma = \frac{1}{4\pi} \left(\frac{\alpha}{2\pi}\right)^2 \frac{g_q^2 y_t^2}{v^2} \frac{g_{DM}^2}{(M_{\text{Med}}^2 - 4m_{DM}^2)^2 + M_{\text{Med}}^2 \Gamma_{\text{Med}}^2} \left| N_c Q_t^2 F_A \left(\frac{m_t^2}{m_{DM}^2} \right) \right|^2, \quad (5.1)$$

$$F_A(\tau) = \tau f(\tau), \text{ and} \quad (5.2)$$

$$f(\tau) = \theta(\tau - 1) \arcsin^2 \left(\frac{1}{\sqrt{\tau}} \right) - \theta(1 - \tau) \frac{1}{4} \left(\log \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} - i\pi \right)^2. \quad (5.3)$$

Here, N_c is the number of colors, Q_t is the top charge, g_q is the coupling to quarks, and y_t/v is the Yukawa coupling divided by the Higgs vacuum expectation. From this cross section formula, we can directly compare with the photon line searches [42, 43] from HESS [44] and FermiLAT [21, 45] in Fig. 5 (left).

The results in Fig. 5 (right) compare the bound from the photon line search with bounds from indirect searches. The photon line bound is less sensitive than, although comparable to, the indirect bounds. In addition, we observe that the current photon line bound approaches sensitivity to a 750 GeV mediator mass for $g_{DM} = g_q = 1$. This is close to the expected sensitivity of the excess of diphoton excess observed at the LHC [41, 46–67]. For a DM coupling of order unity, the potential reach of direct photon searches may provide for a detection of pseudo-scalar mediated DM in the near future.

We additionally consider the projected sensitivities of FermiLAT [45, 68, 69] and of the upgraded HESS experiment [44]. We plot the direct and indirect bounds for these projected results in Fig. 5. From these projected bounds, one observes an extension in the sensitivity to a mediator mass of 1 TeV. We compare these results with relic density bounds in next Section.

6 Experiments vs Relic constraints

Fig. 6 compares cosmological constraints and bounds from direct detection with the 100 TeV collider reach for 1-100 ab^{-1} of data. The reach of the FCC (in blue) extends to $M_{Med} \sim 35$ TeV for a scalar mediator and up to $M_{Med} \sim 15$ TeV for vector and axial-vector mediators.

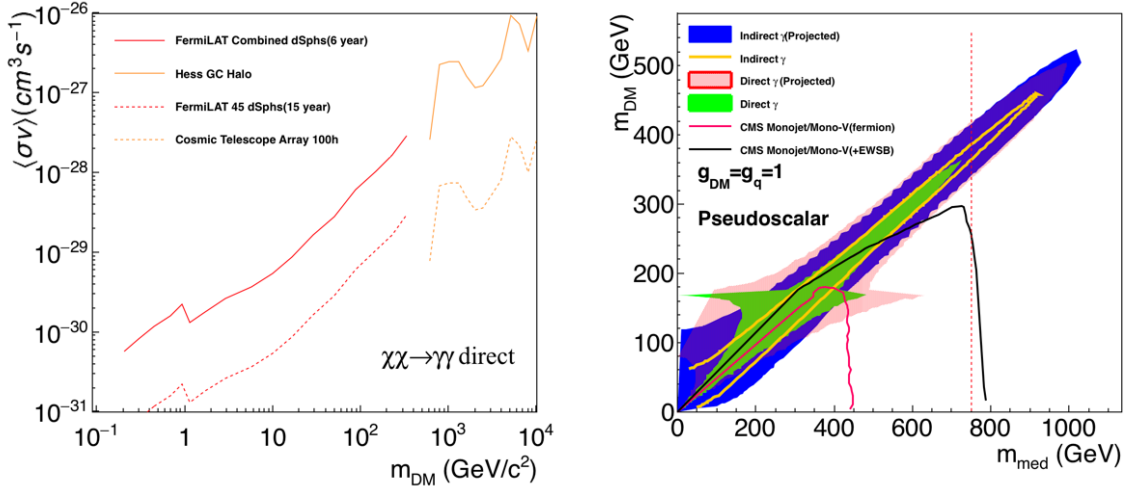


Figure 5. Left: Photon line bounds from FermiLAT [70] and HESS [71] - the dashed lines show the expected updated sensitivity based on 15 years of running for FermiLAT [70] and the Cosmic Telescope Array [72]. The excluded regions are above the curves, *i.e.* the regions with largest cross-section Right: the translation of the FermiLAT, HESS and photon line bounds to the $(M_{\text{Med}}, M_{\text{DM}})$ plane. The yellow line and blue shaded regions correspond to the indirect photon searches and the red and green shaded regions correspond to the photon line searches. The collider bounds from the most sensitive CMS DM search, the combined mono-jet, mono hadronic vector boson search, are also shown [36]. This is presented for both the simplified model where a pseudoscalar coupling to fermions is present (red), and the case where pseudoscalar vector boson couplings are also present (black). For the latter, additional physical effects from the extended model are neglected. A red line at 750 GeV is added to guide the eye.

The collider constraint for a pseudo-scalar mediator is less stringent, reaching only to $M_{\text{Med}} \sim 4$ TeV [73].

Projected FCC constraints do not completely cover the cosmologically allowed region of DM parameter space. Nevertheless, the axial-vector model is almost fully accessible at the FCC, particularly if the large datasets expected for such an experiment are ultimately obtained. A significant fraction of parameter space can also be probed for scalar-mediated models. Pseudo-scalar mediators pose the most significant challenge; as Fig. 6 shows, both FCC and indirect detection experiments are incapable of constraining the parameter space allowed by relic density observations.

The sensitivity of a 100 TeV collider decreases for smaller coupling values, however cosmological constraints are impacted more significantly. This results in tighter collider constraints for all mediators. Direct searches for mediator decays to standard model particles can provide even tighter constraints. Examples of such searches include those for axial mediator decays to dijets and scalar mediator decays to di-photons. Overall, the pseudo-scalar mediator is perhaps the most challenging model to cover with experimental searches - the strongest handles

come from collider based searches.

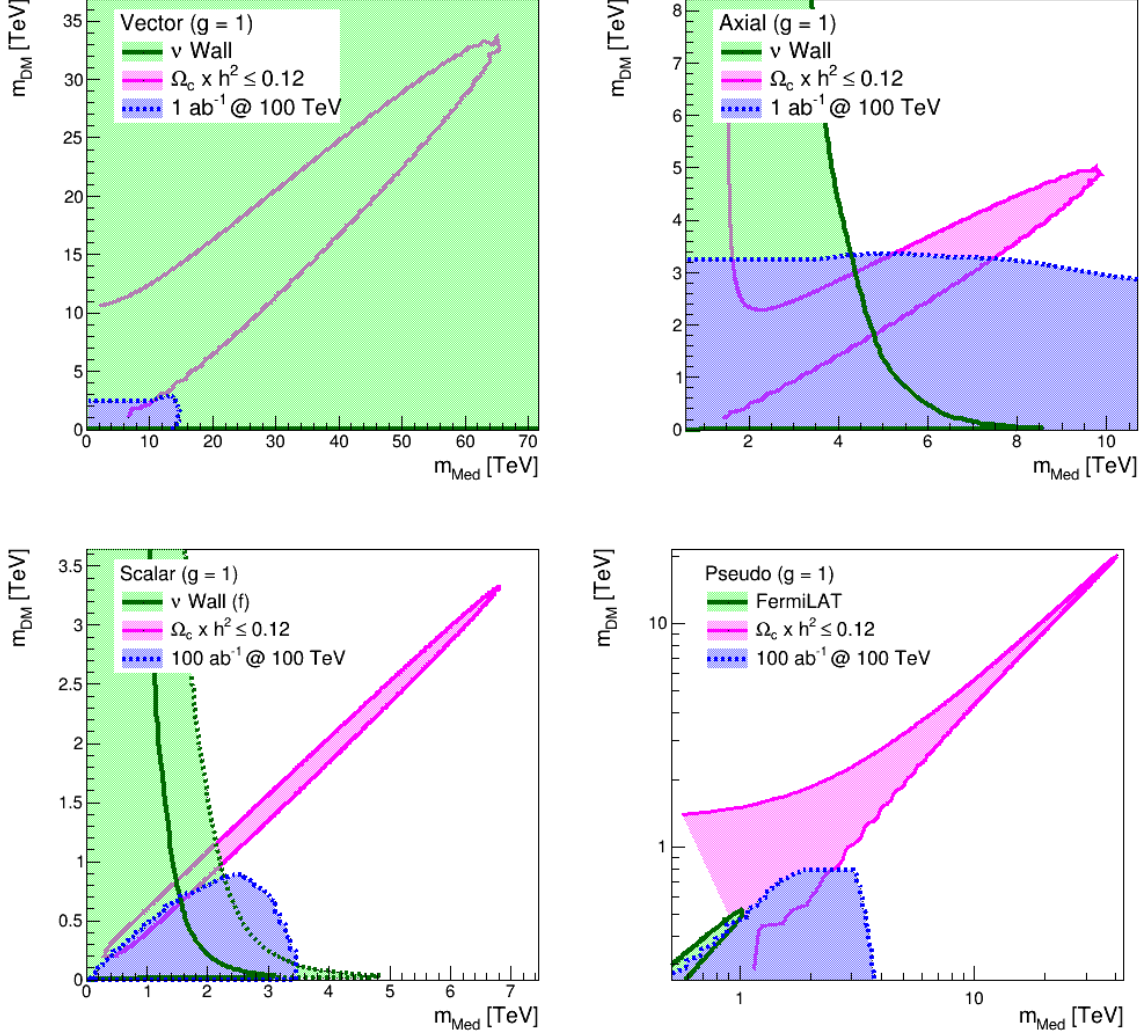


Figure 6. Pink: regions with $\Omega_c \times h^2 \leq 0.12$ for the vector, axial-vector, scalar and pseudo-scalar mediators, for coupling $g_q = g_{SM} = 1$, and $g_{DM} = 1$. Green: neutrino wall. Blue: expected sensitivity for a 100 TeV collider with 1 ab^{-1} [73].

7 Conclusions

Cosmological constraints have been shown for the class of simplified mediator models used in searches at the LHC. The numerical predictions of relic DM abundance are calculated using **MadDM**, which uses the **MadGraph** simplified models to estimate the cross-section of the $\chi\chi \rightarrow SM$ annihilation within the standard model of cosmology.

For DM and mediator masses accessible at the LHC, the shapes of the relic constraints are attributed to suppressed mediator to dark matter decays when $M_{DM} < M_t$ and enhanced resonant annihilation for $M_{Med} \sim 2 \times M_{DM}$. Cosmological constraints have also been shown for the wider mass ranges reachable at possible future colliders. Masses consistent with cosmological observations typically reach up to 10-100 TeV. The shapes of the bounds in this wide mass range are attributed to resonant annihilation and the width of the mediators.

The LHC has sensitivity to a small part of the cosmologically preferred parameter space for the models considered. A 100 TeV collider, on the other hand, has significant sensitivity in the full parameter space allowed by relic density constraints. Significant coverage is obtained for scalar and axial-vector mediators, whereas the pseudo-scalar mediated model is rather difficult to constrain.

The cosmological constraints presented in this document are available for the collider searches by the LHC Collaborations at [74].

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References

- [1] **Planck** Collaboration, J. Tauber, M. Bersanelli, J. M. Lamarre, G. Efstathiou, C. Lawrence, F. Bouchet, E. Martinez-Gonzalez, S. Matarrese, D. Scott, M. White, et al., *The Scientific programme of Planck*, [astro-ph/0604069](#).
- [2] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: Evidence, candidates and constraints*, *Phys. Rept.* **405** (2005) 279–390, [[hep-ph/0404175](#)].
- [3] D. Abercrombie et al., *Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum*, [1507.00966](#).
- [4] G. Busoni et al., *Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter*, [1603.04156](#).
- [5] N. Arkani-Hamed, T. Han, M. Mangano, and L.-T. Wang, *Physics Opportunities of a 100 TeV Proton-Proton Collider*, [1511.06495](#).

- [6] J. M. Campbell et al., *Working Group Report: Quantum Chromodynamics*, in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, 2013. [1310.5189](#).
- [7] I. Hinchliffe, A. Kotwal, M. L. Mangano, C. Quigg, and L.-T. Wang, *Luminosity goals for a 100-TeV pp collider*, *Int. J. Mod. Phys. A* **30** (2015), no. 23 1544002, [[1504.06108](#)].
- [8] T. G. Rizzo, *Mass Reach Scaling for Future Hadron Colliders*, *Eur. Phys. J. C* **75** (2015), no. 4 161, [[1501.05583](#)].
- [9] X. Zhang, *Operator analysis for the higgs potential and cosmological bound on the higgs-boson mass*, *Phys. Rev. D* **47** (Apr, 1993) 3065–3067.
- [10] P. Cushman et al., *Working Group Report: WIMP Dark Matter Direct Detection*, in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013*, 2013. [1310.8327](#).
- [11] M. Schumann, L. Baudis, L. Btikofer, A. Kish, and M. Selvi, *Dark matter sensitivity of multi-ton liquid xenon detectors*, *JCAP* **1510** (2015), no. 10 016, [[1506.08309](#)].
- [12] **LZ** Collaboration, D. S. Akerib et al., *LUX-ZEPLIN (LZ) Conceptual Design Report*, [1509.02910](#).
- [13] C. E. Aalseth et al., *The DarkSide Multiton Detector for the Direct Dark Matter Search*, *Adv. High Energy Phys.* **2015** (2015) 541362.
- [14] **XENON100** Collaboration, E. Aprile et al., *Limits on spin-dependent WIMP-nucleon cross sections from 225 live days of XENON100 data*, *Phys. Rev. Lett.* **111** (2013), no. 2 021301, [[1301.6620](#)].
- [15] **LUX** Collaboration, D. S. Akerib et al., *First spin-dependent WIMP-nucleon cross section limits from the LUX experiment*, [1602.03489](#).
- [16] M. Low and L.-T. Wang, *Neutralino dark matter at 14 TeV and 100 TeV*, *JHEP* **08** (2014) 161, [[1404.0682](#)].
- [17] J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, and M. Takeuchi, *Relic neutralino surface at a 100 TeV collider*, *Phys. Rev. D* **91** (2015) 054015, [[1412.4789](#)].
- [18] Q.-F. Xiang, X.-J. Bi, P.-F. Yin, and Z.-H. Yu, *Searches for dark matter signals in simplified models at future hadron colliders*, *Phys. Rev. D* **91** (2015) 095020, [[1503.02931](#)].
- [19] A. Freitas, S. Westhoff, and J. Zupan, *Integrating in the Higgs Portal to Fermion Dark Matter*, *JHEP* **09** (2015) 015, [[1506.04149](#)].
- [20] M. Cirelli, F. Sala, and M. Taoso, *Wino-like Minimal Dark Matter and future colliders*, *JHEP* **10** (2014) 033, [[1407.7058](#)]. [Erratum: JHEP01,041(2015)]. [CST ‘14].
- [21] M. R. Buckley, D. Feld, and D. Goncalves, *Scalar Simplified Models for Dark Matter*, *Phys. Rev. D* **91** (2015) 015017, [[1410.6497](#)].
- [22] J. Abdallah et al., *Simplified Models for Dark Matter and Missing Energy Searches at the LHC*, [1409.2893](#).
- [23] S. A. Malik et al., *Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments*, *Phys. Dark Univ.* **9-10** (2015) 51–58, [[1409.4075](#)].

- [24] O. Buchmuller, M. J. Dolan, S. A. Malik, and C. McCabe, *Characterising dark matter searches at colliders and direct detection experiments: Vector mediators*, *JHEP* **01** (2015) 037, [[1407.8257](#)].
- [25] U. Haisch and E. Re, *Simplified dark matter top-quark interactions at the LHC*, *JHEP* **06** (2015) 078, [[1503.00691](#)].
- [26] M. Chala, F. Kahlhoefer, M. McCullough, G. Nardini, and K. Schmidt-Hoberg, *Constraining Dark Sectors with Monojets and Dijets*, *JHEP* **07** (2015) 089, [[1503.05916](#)].
- [27] V. V. Khoze, G. Ro, and M. Spannowsky, *Spectroscopy of scalar mediators to dark matter at the LHC and at 100 TeV*, *Phys. Rev.* **D92** (2015), no. 7 075006, [[1505.03019](#)].
- [28] O. Buchmuller, S. A. Malik, C. McCabe, and B. Penning, *Constraining Dark Matter Interactions with Pseudoscalar and Scalar Mediators Using Collider Searches for Multijets plus Missing Transverse Energy*, *Phys. Rev. Lett.* **115** (2015), no. 18 181802, [[1505.07826](#)].
- [29] J. Fan, S. M. Koushiappas, and G. Landsberg, *Pseudoscalar Portal Dark Matter and New Signatures of Vector-like Fermions*, *JHEP* **01** (2016) 111, [[1507.06993](#)].
- [30] O. Lebedev and Y. Mambrini, *Axial dark matter: The case for an invisible Z*, *Phys. Lett.* **B734** (2014) 350–353, [[1403.4837](#)].
- [31] J. Abdallah et al., *Simplified Models for Dark Matter Searches at the LHC*, *Phys. Dark Univ.* **9-10** (2015) 8–23, [[1506.03116](#)].
- [32] G. D’Ambrosio, G. F. Giudice, G. Isidori, and A. Strumia, *Minimal flavor violation: An Effective field theory approach*, *Nucl. Phys.* **B645** (2002) 155–187, [[hep-ph/0207036](#)].
- [33] M. Backovic, K. Kong, and M. McCaskey, *MadDM v.1.0: Computation of Dark Matter Relic Abundance Using MadGraph5*, *Physics of the Dark Universe* **5-6** (2014) 18–28, [[1308.4955](#)].
- [34] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128, [[1106.0522](#)].
- [35] **Planck** Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, [1502.01589](#).
- [36] **CMS** Collaboration, *Search for New Physics in the V/jet + MET final state*, Tech. Rep. CMS-PAS-EXO-12-055, CERN, Geneva, 2015.
- [37] **CMS** Collaboration, *Search for dark matter with jets and missing transverse energy at 13 TeV*, Tech. Rep. CMS-PAS-EXO-15-003, CERN, Geneva, 2016.
- [38] *Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC*, Tech. Rep. ATLAS-CONF-2015-080, CERN, Geneva, Dec, 2015.
- [39] F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, *Implications of unitarity and gauge invariance for simplified dark matter models*, *JHEP* **02** (2016) 016, [[1510.02110](#)]. [[JHEP02,016\(2016\)](#)].
- [40] P. Harris, V. V. Khoze, M. Spannowsky, and C. Williams, *Constraining Dark Sectors at Colliders: Beyond the Effective Theory Approach*, *Phys. Rev.* **D91** (2015) 055009, [[1411.0535](#)].
- [41] M. Low, A. Tesi, and L.-T. Wang, *A pseudoscalar decaying to photon pairs in the early LHC Run 2 data*, *JHEP* **03** (2016) 108, [[1512.05328](#)].

- [42] J. Fan and M. Reece, *In Wino Veritas? Indirect Searches Shed Light on Neutralino Dark Matter*, *JHEP* **1310** (2013) 124, [[1307.4400](#)].
- [43] T. Cohen, M. Lisanti, A. Pierce, and T. R. Slatyer, *Wino Dark Matter Under Siege*, *JCAP* **1310** (2013) 061, [[1307.4082](#)].
- [44] **H.E.S.S. Collaboration** Collaboration, A. Abramowski et al., *Search for photon line-like signatures from Dark Matter annihilations with H.E.S.S.*, *Phys.Rev.Lett.* **110** (2013) 041301, [[1301.1173](#)].
- [45] **Fermi-LAT** Collaboration, M. Ackermann et al., *Updated search for spectral lines from Galactic dark matter interactions with pass 8 data from the Fermi Large Area Telescope*, *Phys. Rev. D* **91** (2015), no. 12 122002, [[1506.00013](#)].
- [46] *Search for resonances in diphoton events with the ATLAS detector at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATLAS-CONF-2016-018, CERN, Geneva, Mar, 2016.
- [47] **CMS** Collaboration, *Search for new physics in high mass diphoton events in 3.3 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV and combined interpretation of searches at 8 TeV and 13 TeV*, Tech. Rep. CMS-PAS-EXO-16-018, CERN, Geneva, 2016.
- [48] M. Backovic, A. Mariotti, and D. Redigolo, *Di-photon excess illuminates Dark Matter*, [1512.04917](#).
- [49] Y. Mambrini, G. Arcadi, and A. Djouadi, *The LHC diphoton resonance and dark matter*, [1512.04913](#).
- [50] S. Di Chiara, A. Hektor, K. Kannike, L. Marzola, and M. Raidal, *Large loop-coupling enhancement of a 750 GeV pseudoscalar from a light dark sector*, [1603.07263](#).
- [51] M. Redi, A. Strumia, A. Tesi, and E. Vigiani, *Di-photon resonance and Dark Matter as heavy pions*, [1602.07297](#).
- [52] S.-F. Ge, H.-J. He, J. Ren, and Z.-Z. Xianyu, *Realizing Dark Matter and Higgs Inflation in Light of LHC Diphoton Excess*, [1602.01801](#).
- [53] V. De Romeri, J. S. Kim, V. Martin-Lozano, K. Rolbiecki, and R. R. de Austri, *Confronting dark matter with the diphoton excess from a parent resonance decay*, [1603.04479](#).
- [54] A. Bharucha, A. Djouadi, and A. Goudelis, *Threshold enhancement of diphoton resonances*, [1603.04464](#).
- [55] A. Salvio, F. Staub, A. Strumia, and A. Urbano, *On the maximal diphoton width*, [1602.01460](#).
- [56] A. Hektor and L. Marzola, *Di-photon excess at LHC and the gamma ray excess at the Galactic Centre*, [1602.00004](#).
- [57] F. D’Eramo, J. de Vries, and P. Panci, *A 750 GeV Portal: LHC Phenomenology and Dark Matter Candidates*, [1601.01571](#).
- [58] F. F. Deppisch, C. Hati, S. Patra, P. Pritimita, and U. Sarkar, *Implications of the diphoton excess on Left-Right models and gauge unification*, [1601.00952](#).
- [59] D. Palle, *On the possible new 750 GeV heavy boson resonance at the LHC*, [1601.00618](#).
- [60] K. Ghorbani and H. Ghorbani, *The 750 GeV Diphoton Excess from a Pseudoscalar in Fermionic Dark Matter Scenario*, [1601.00602](#).

- [61] X.-J. Huang, W.-H. Zhang, and Y.-F. Zhou, *A 750 GeV dark matter messenger at the Galactic Center*, [1512.08992](#).
- [62] S. Moretti and K. Yagyu, *The 750 GeV diphoton excess and its explanation in 2-Higgs Doublet Models with a real inert scalar multiplet*, [1512.07462](#).
- [63] P. S. B. Dev and D. Teresi, *Asymmetric Dark Matter in the Sun and the Diphoton Excess at the LHC*, [1512.07243](#).
- [64] J.-C. Park and S. C. Park, *Indirect signature of dark matter with the diphoton resonance at 750 GeV*, [1512.08117](#).
- [65] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, *What is the gamma gamma resonance at 750 GeV?*, [1512.04933](#).
- [66] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz, and T. You, *On the Interpretation of a Possible ~ 750 GeV Particle Decaying into $\gamma\gamma$* , [1512.05327](#).
- [67] Y. Bai, J. Berger, and R. Lu, *A 750 GeV Dark Pion: Cousin of a Dark G-parity-odd WIMP*, [1512.05779](#).
- [68] C. Jin, *Dark matter particle explorer the first chinese cosmic ray and hard gamma-ray detector in space*, *Chinese journal of space science* (2014).
- [69] V. I. Dokuchaev and Yu. N. Eroshenko, *Physical laboratory at the center of the Galaxy*, *Phys. Usp.* **58** (2015) 772–784, [[1512.02943](#)].
- [70] **DES, Fermi-LAT** Collaboration, A. Drlica-Wagner et al., *Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data*, *Astrophys. J.* **809** (2015), no. 1 L4, [[1503.02632](#)].
- [71] **HESS** Collaboration, A. Abramowski et al., *Constraints on an Annihilation Signal from a Core of Constant Dark Matter Density around the Milky Way Center with H.E.S.S.*, *Phys. Rev. Lett.* **114** (2015), no. 8 081301, [[1502.03244](#)].
- [72] M. Actis, G. Agnetta, F. Aharonian, A. Akhperjanian, J. Aleksić, E. Aliu, D. Allan, I. Allekotte, F. Antico, L. A. Antonelli, and et al., *Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy*, *Experimental Astronomy* **32** (Dec., 2011) 193–316, [[1008.3703](#)].
- [73] P. Harris, V. V. Khoze, M. Spannowsky, and C. Williams, *Closing up on Dark Sectors at Colliders: from 14 to 100 TeV*, *Phys. Rev.* **D93** (2016), no. 5 054030, [[1509.02904](#)].
- [74] Relic Density Calculation for LHC DM Searches, cern.ch/LPCC/index.php?pag=dm-wg-docs, .